# NONDESTRUCTIVE EVALUATION OF FIBERGLASS USING CHOLESTERIC LIQUID CRYSTALS: REVIEW OF TECHNIQUES AND INDUSTRIAL APPLICATIONS

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SUBMITTED IN PARTIAL FULFILLMENT
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## Abstract

Based on this investigation, nondestructive evaluation of fiberglass with colesteric liquid crystals can provide a simple test for the evaluation of fiberglass boat hulls. This paper reviews the various techniques involved in liquid crystal thermography and fiberglass specimen construction. Equipment was designed and built to test fiberglass specimens under different lighting conditions. The equipment built will also aid in the determination of the optimal heat flux for the detection of minute flaws in fiberglass specimens using thermal testing with cholesteric liquid crystals. A special fiberglass panel with 108 flaws of known size and location was built to help establish the lower limit of resolution of different crystal blends and thermal test procedures.

This research was exploratory and initiatory. The equipment and specimens built for this research should help in the refinement of this thermal testing technique. It is hoped that the project will be continued until a suitable field test for the nondestructive evaluation of fiberglass is developed.

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# FOREWORD

Composites enable the design of unique materials which combine high strength and high stiffness to an extent unattainable through conventional metallurgical practices. Fiber composites have a high strength/weight ratio which makes them attractive materials where increased performance can be achieved through weight reduction, such as in boat building. Most fiber composites used in boat construction are fiberglass layups. However, high performance sailboats and powerboats are currently being built with kevlar, dynel, graphite and other sophisticated and expensive fiber materials. Their use is restricted to high performance applications and is done by very few manufacturers. The capital investment necessary to manufacture boats with fiberglass is lower than that previously needed to build a boat out of wood or aluminum. As a consequence, it has had a great impact on the boating industry. The versatility of fiberglass allows it to be molded to many shapes and material specifications. This, combined with the relative ease of manufacture, has attracted many builders to the boat industry. Today some 2500 - 3000 builders build pleasure crafts which range in size from 9 - 100 feet and are classified into various categories, such as inboards, outboards, inboard-outboards, ATV's, airboats, sailboats, houseboats, custom boats, and canoes and kayaks.[1]

There are no enforceable federal regulations regarding the construction of the fiberglass lay-up for pleasure boats. Guide-

lines are set by the American Bureau of Shipping[2] and the American Boat and Yacht Council[3], but both of these are quite general and only specify that the builder submit for review, a fabrication process description before the lay-up is commenced. Due to the lack of regulations large variations in the qulity of design and construction of pleasure crafts exists. Deviation in properties for composite materials on multiple tests is somewhat greater than that considered acceptable for established metal technology.

Under the Federal Boat Safety Act of 1971, the Coast Guard is given the power to require the manufacturer of a boat which contains a safety defect to notify all purchasers and make the necessary repairs at the manufacturer's expense. The major obstacle to effective enforcement regarding structural integrity is the lack of quantitative inexpensive NDE techniques which can be broadly required by the Coast Guard.

Pleasure boat manufacturers and the boating public have no simple cost-effective method for assessing the structural integrity of fiberglass pleasure craft. Consequently, substandard craft may be sold or transferred as governmental agencies are unable to establish quantitative regulations. Most NDE techniques which are employed by the aircraft industry to test composite structures are expensive, complicated and equipment-intensive.

What this research project aims to establish is:

1) A cost-effective NDE technique for boat manufacturers

prior to craft delivery;

2) A procedure to assist governmental agencies in establishing quantitative structural criteria for pleasure craft;

3) A technique to aid marine surveyors in conducting "Condition Surveys" which form an important basis for craft insurability;

4) A simple test for boat owners for assessing the structural integrity of their boats;

5) Laboratory apparatus and techniques which will help meet the aims listed above.

# INTRODUCTION

The purpose of this research was to develop an inexpensive easily utilized nondestructive evaluation (NDE) test for the evaluation of fiberglass structures.

Most defects common to composite layups such as voids, delaminations, uncured matrix, improper interface bonds, improper resin-matrix ratio and even the neglect of reinforcing layers, are internal in nature and are usually undistinguishable from an undamaged composite. Nondestructive evaluation (NDE) techniques must be used to detect the presence of potentially hazardous defects. Methods for establishing the quality of the manufactured composite by NDE must be developed to a high level of assurance for all types of fiber-matric composite layups. Although the science of NDE is very broad, certain categories, each containing a number of NDE techniques, offer characteristic capabilities which are likely to be of essential value in revealing the types of flaws which are most prevalent in composite materials. NDE method selection is generally based on part geometry and composition, defect size, location, orientation and availability of test equipment. Very often more than one NDE method is used because different conditions and defects are revealed. Some NDE methods which are likely to prove most valuable in evaluating fiber composites are summarized in Table 1.

The first step in the nondestructive evaluation is the visual

inspection of the fiber composite layup. The method for identification and classification of visual defects in glass reinforced laminates is covered in ASTM D2563; allowable defects and their acceptance levels are included in table 2. All composite parts have to be inspected for conformance with dimensions and tolerances specified of the drawings. Critical areas are defined by ASTM as those areas in which the presence of imperfections is considered to be most detrimental, these areas shall be free of all defects listed in Table 2. The defects in noncritical areas which by nature, content, or frequency do not affect serviceability of the part are designated as allowable defects. Allowable defects must comply with the acceptance levels described in Table 2. The presence of these defects must be indicated in the product drawings. The type of test I am aiming for is one that can be used at any remote location, such as a dry dock or a boat trailer (see fig. 1.), and under a variety of environmental conditions. This would result in a test which can aid boat users and as a supplement to visual inspection for analyzing the structural integrity of fiberglass boats.

Nondestructive evaluation of fiber composites with cholesteric liquid crystals is a cheap, accurate and easily utilized process for the evaluation of fiberglass structures. Previous research using cholesteric liquid crystals have found them to be successful tools in the analysis of bonds, leak detection, penetrant detection, thermal definition of cracks and the analysis of honeycomb composites. The chemical properties of the

liquid crystals are discussed in Appendix B. The first step of the research was to develop techniques and equipment for a field test that can be used for the thermographic evaluation of commercial fiberglass structures. The experiments I have performed and the equipmment I built for this project should be extremely useful for the quantitative analysis of the variety of defects and material properties that can be obtained from such techniques.

My research in liquid crystal thermography (LCT) can be broken down into three components, the test jig and recording equipment, specimen design and construction and the liquid crystal system. I hope this thesis can serve as a guide for those doing further research in the area of liquid crystal thermography.

## EXPERIMENTAL PROCEDURE

LCT, when properly executed, allows for the simultaneous detection of rapidly changing departures at a large number of points. The area which can be tested effectively depends on the area over which constant intensity heat can be applied and monitored. The test stand which I built for this research is illustrated in figure 2. This jig is designed for the irradiation of large surface ares with a uniform intensity light. The angle and intensity of the lights and the size of the uniform test area can be controlled by moving the lamps relative to the area to be tested. The lights used on this jig are Smith Victor Model 750/1000 watt quartz-iodine studio lamps and are mounted on a set of rails that allows them to be placed anywhere within the shaded area in figure 2. The flexibility provided by this light jig can aid, in later research projects, to find the optimal heat flux pattern for the detection of minute flaws in fiberglass specimens.

Another objective of this experimental set-up was to accommodate specimens of many sizes. Liquid crystal thermography (LCT) can be a useful tool for the evaluation of any material whose thermal response is significantly altered by the presence of material discontinuities, to the point where it becomes present at the surface as a variation in the thermal map. Some of the specimens tested were 1" x 12" strips of fiberglass, others consisted of flat panels (7" x 7"). The specimen holder

(fig. 3) consists of a highly articulated adjustable microscope mount built by American Optical Instrument Company. Specimens are held on a plane which can be placed and secured in a large number of positions without having to be unmounted or touched. This is extremely convenient for LCT since you avoid disturbing the liquid crystal layer whenever the specimen needs to be moved or adjusted. The mounting plate is 4" x 19" and can also be used to hold stopwatches, thermometer probes and identification labels.

The open design of the test stand permits observation of the LCT from many angles. Permanent records of liquid crystal thermograms can be made on color film. Several considerations must be made in color film selection as they have different film speed, resolution and color response. Higher film speeds (ASA) allow the use of higher F-stops that provide a greater depth of field. High ASA films should be used if the application involves curved surfaces that are difficult to focus entirely or where the light sources are located more than 3' from the thermogram. Higher film speeds lose resolution though not significantly enough to affect thermogram interpreation. For monitoring during heat up Kodachrome ASA 100 is adequate. The camera used for this project is a Nikon FM with a 135 mm f/2.8 Autopromaster lens. There are a couple of drawbacks to this photographic set-up:

1) The promaster lens does not couple with the Nikon light meter so that f-stop changes on the lens are not automatically sensed by the light meter, thus

correct exposure has to be set manually.

2) The 135 mm lens is too long, so it does not allow for close-up photos of the specimen. A couple of suggestions on the recording equipment are to get a 50 mm NIKON MACRO Lens and a motor drive for the camera.

In addition to the photographic recording equipment we used a portable digital thermometer (Precision Digital Model 521) to monitor the temperature of the specimen surface during the test. The probe used was an attachable surface probe (YSI Series 700 Thermistor Probe). It consists of a 3/8" dia. stainless steel cup, epoxy backed. The time constant of the probe is 1.1 seconds. The time constant is a standard measure of probe response time; it is the time required for a probe to read 63% of a newly impressed temperature. The next step in temperature monitoring will be to connect the thermometer to an X-Y plotter so that we get time vs. temperature graphs of every test. I would also advise using an air temperature probe to get accurate measurements of the effects of ambient temperature on LCT.

## Specimen Design

The fiberglass specimens used in this research were duplicates of the lay-up used in the construction of single skin hulls for high performance yachts[4]. The main objective of the specimen was to introduce a number of flaws of known type, size and location, to determine the lower limit of resolution of our current LCT test. The specimen was built of seven layers of

glass in a mold shaped as a scale model of popular deep-vee hull designs (fig. 4)[6]. This shape was useful in analyzing the usefulness of LCT for testing surfaces of different sizes and orientations. The construction of fiberglass panels is described in Appendix A. The main (fig. 5) panel contains 108 flaws made to represent small air voids or cracks in the interior of a boat hull. The flaws come in six sizes (.20 - .28 - .56 - .63 - .80 - 1.05 mm diameter) and are built into the specimen in groups of six with lengths of 1" - 3/4" - 1/2" depending on their location on the panel. The location of the flaws varies also; they are located at the interface between the glass layers (fig. 6). These flaws are made from micropipettes are more representative of internal flaws of fiberglass than the air voids used in previous tests. The panel was built with a black gel coat so that liquid crystals can be applied directly without a backup paint. Molded fiber glass, whether in a boat, car body, furniture or other items, is easily repaired with polyester resin and fiber glass mat and/or cloth. Sometimes the secondary bond between the patch and the hull is not perfect and may fail while in operation. LCT can be useful for the detection of air gaps in the secondary bond as well as internal cracks which may have gone undetected. The presence of voids in adhesive bonds which may significantly weaken the structure will also decrease the local thermal diffusivity of the bond line. As the surface, which is coated with the liquid crystals, is heated, the face sheet (over areas with poorer heat transfer) will heat more rapidly than the

adjacent well-bonded areas.

Since the surface temperature of a material undergoing thermal testing is only a few degrees above room temperature a direct photographic method cannot be used to detect the temperature differences because no photographic material exists which is sensitive to the long wavelength (8000 Angstroms - 10,000 Angstroms) region in question. Thermal gradients can be detected and evaluated by various methods most common of which are the use of thermal sensitive coatings and infra-red inspection. We focused our attention on the use of temperature-sensitive cholesteric liquid crystals for the evaluation of thermal gradients associated with material discontinuities.

## Liquid Crystals

Liquid crystals are described in Appendix B. Thermal testing with cholerteric liquid crystals can be particularly useful in the evaluation of odd-shaped surfaces, and irregular contours which cannot be assessed by other NDE methods. Liquid crystal thermography can be useful for monitoring thermal gradients in any material as long as the surface is smooth and has been painted with black paint. With liquid crystals it is possible to make direct observations in high ambient light of small thermal gradients near room temperature. Their simplicity, high sensitivity and speed of response make them readily adaptable to the varied requirements of laboratory and process development investigations.

Liquid crystals should be sprayed uniformly over the surface of the specimen. Potting depths slow response time and wash out resolution considerably, and therefore, one must avoid touching the surface of a coated specimen since streaks and marks also affect the response of the crystals. Liquid crystals can be washed off with acetone, Ajax or any similar detergent; make sure all the old crystals are washed off before applying a new coat. Specimens should be dry and free of dust particles before they are coated with crystals, as these will also adversely affect the response of the blends. Once a specimen is coated the same blend can be used repeatedly approximately 25 times. The coat can be left on the specimen for several days as long as it is not damaged by dust or wind exposure.

# CONCLUSIONS AND RECOMMENDATIONS

Liquid crystal thermography can be a useful method for the nondestructive evaluation of fiberglass. The equipment and specimens prepared in this thesis are designed to conduct research to develop a field test for the evaluation of boat hulls. A variable heat source that can apply uniform heat over large areas has been built (and is now in 3-365). This test stand should be used to find the optimal heat flux for the detection of very small flaws in fiberglass. The jig has been designed so that it is easily adjusted and serviced. A fiberglass panel with 108 flaws of known size and location was also built and testd. The present system was only capable of detecting 8 of these flaws, those of the outermost layers. The light jig and fiberglass panel can be used quantitaviely to rate the effectiveness of different crystal blends under different test conditions. I hope this research is continued and that this thesis can serve as a good starting point and guide for future research projects in Liquid Crystal Thermography.

## APPENDIX A. Building a fiberglass specimen.

The construction of a fiberglass panel, or lay-up, is an elaborate process requiring careful attention to a large number of factors that affect the quality of the panel. Fiberglass specimens can be built of any size, shape and strength with good consistency as long as the lay up is carefully planned and executed. There are two basic types of fiberglass panels: single skin and sandwich construction. Construction of sandwich panels is more difficult than single skin because of the steps necessary to ensure a good bond between the skins and core. There are three basic core materials in general use today: (1) Those incorporating light weight cores of foam or balsa, in which the bending is resisted almost entirely by the skins, due to the very low modulus of the core. (2) Those incorporating cores which are effective in bending, such as plywood, which has a modulus of elasticity similar to that of FRP. For this type the design of the panel must be based on the lower strength of the plywood. (3) Those incorporating thin FRP webs to separate the faces. This type of construction permits the use of thinner panels since the shear strength of the webs is far higher than that of foam or balsa. The voids between the shear webs are generally filled with low density foam (2 pounds per square foot) both to provide a mold surface for laying of the webs and to prevent their buckling[6].

These are illustrated in figure 7. For a material of equal

stiffness, a sandwich panel will be both lighter and require less depth than a single skin with frames. Sandwich construction is generally limited to large flat surfaces such as decks, bulkheads and cabin tops. The stiffness of sandwich panels is particularly advantageous in constructing walking surfaces where the flexibility of thin single skin FRP panels would be unacceptable.

Single skin panels are made of successive layers of glass reinforcement soaked in a resin matrix. Common layups consist of alternate layers of mat and woven roving repeated 3 or 4 times. Mat or chopped mat, consists of randomly oriented chopped glass fibers bonded into sheets with a light adhesive. Chopped mat comes in various weights (1/2, 3/4, 1, 1 1/2, 2 oz./sq. ft.) and fiber lengths (3/4, 1, 1 3/4, 2 in.), it usually comes in rolls and is commonly bought by the square yard. Chopped mat requires careful handling to prevent the glass fibers from becoming embedded in the skin. The women roving (rov) or fiberglass cloth consists of long bundles of glass fibers woven into a cloth. It comes in several weights (10-40 oz./sq. yard), the one most commonly used in hull construction being the 24 oz. size; for repairs a lighter cloth -- 12-16 oz. -- is preferable.

## Mold Preparation

The first step in the construction of a fiberglass panel is the design and construction of a mold. A panel may be built in two ways: into a female mold or onto a male mold. In both cases the construction is basically the same, the only difference being

in whether you begin or end with the gel coat. Molds can be made out of wood, aluminum, or fiberglass; the only requirement is that they be stiff (so that they don't deform during lay-up) and easy to work with. I preferred to work with aluminum female molds be cause we did not have the necessary equipment for the proper application of a gel coat. With a female mold, the first layer applied is the outer gel coat; before application the surface should be polished smooth since any scratches or pits will appear on the outer surface of the panel. Once a mold is polished it should be waxed several times (using ceara mold wax) and then sprayed with a mold release, making sure to keep the mold clean and free from dust until you are ready to apply to gel coat. Preparation of the surface is all-important. If it is done right, you will never have to do it again...so take you time and work carefully.

The panel is built from the outside in. I selected a seven-ply construction (4 mats, 3 rov) similar to that used by most boat builders for craft from 20-60 ft. The first panels were made flat; more recent panels were scale models of single skin power boat hulls. I strongly recommend that one practice with small flat panels before attempting to build a complex specimen.

## Flaw Design

The key to a successful specimen construction is organization and practice. First, the materials for the panel have to be selected and arranged in their proper sequence. The reinforcing

material can be cut to size using long scissors and stacked in the correct sequence (with paper between the layers to prevent separation of fibers). At this point one should also design and prepare the flaws that will be introduced in the specimens. A record should be kept of the flaw types, sizes, locations that will be included in the specimen; this will help later when analyzing the thermographs. There are many ways to introduce flaws in a fiberglass specimen but few of them can produce accurate and consistent results. Initial flaws consisted of voids made by cutting out a section or several sections out of the layers and creating an air void in the lay-up. This approach has several drawbacks:

1) resin flows in the vacant area filling up the void unless one pre-cures the boundaries of the flaw;
2) although this type of flaw is easily detectable with liquid crystals it is unlikely that it ever occurs in real situations.

Using this technique I placed voids of only one ply thickness (approximately 1/20") and was able to detect them successfully at depths of up to 3/16".

Another technique for introducing flaws of known size and location is to use small glass tubes, micropipettes. The tubes are first measured to determine the internal diameter, then they are cut to specific lengths and sealed with wax. I noticed that the tubes tend to fill with resin by capillary action rendering them useless as flaws; this is why I seal the ends with wax.

There are several advantages to using glass tubes as flaws, such as:

1) ease of construction,
2) variety and consistency of size (0.2-1 mm.),
3) cut to any size and placed at any interface,
4) their precise size and location can be recorded as they are placed in the lay up.

The drawbacks are:

1) they tend to fill up with resin,
2) they break easily when handlng and during lay-up.

Glass tubes can be used to model small air bubbles and hair line cracks inside a composite. One of the reasons I chose to use glass tubes was that they were available in sizes much smaller than any of the flaws which were previously detected using colicry hence we could set a lower limit of resolution for our test as well as a goal for further research in the area.

For the matrix, one can choose either polyester or epoxy resins. Polyester resin will do a fine job under most conditions and is most economical. Epoxy resin costs more, but offers greater adhesion and superior strength where needed for special conditions. In addition, there are coloring agents available for adding to the polyester resin or tinting the premixed colors normally added to the finish coat only. A maximum of 1 oz. of coloring pigment should be used for one (1) quart of resin. Special pigments are used with epoxy systems. Another major difference is the setting times. Polyester resins can harden in

five minutes and be fully cured within an hour; epoxy resins (which are usually used in large boat construction) require at least 4 hours to set and up to 24 hours to be fully cured.

Where to Work

Work should be done under cover, if possible, or shaded if out-of-doors. If working when the temperature is below 60 degrees Fahrenheit, a well-ventilated and heated shop is preferred. DO NOT WORK IN DIRECT SUNLIGHT, as this accelerates the curing of the resin and can cause a distortion of the finish. A temperature of 70 to 80 degrees Fahrenheit is ideal. The mold or other surfaces you are working on should also be at this temperature.

Getting Ready

Make sure the mold has been waxed and sprayed before doing the lay-up. Prepare all your tools and materials before mixing any resin. This should include:

3 pairs of plastic gloves (at least)

3 beakers 500 or 1000 ml; have one for mixing resin, one with acetone and 1 spare.

2 brushes, 1 1/2" wide with brush hair cut to 3/4" length

1 flat roller

1 grooved roller

1 mold (waxed and sprayed)

5 mats (cut to size) (one extra)

3 rovings (cut to size)

epoxy resin -- DER 331 or similar

hardener -- VERSAMID 140 or similar

pigments and mixing rod

paper towels

wax paper

flaws and notepads

If you are working with epoxy resin, as I did, you should apply the "gel coat" first and let it dry overnight. A gel coat usually consists of tougher epoxy resin and is the outer layer of a boat, a pigmented epoxy resin was used for our specimens since gel coats are expensive and very difficult to work with.

On cold days, use more hardener to insure curing; on warm days, cut down on the hardener to keep the resin from curing too soon. When applying the gel coat use equal amounts of resin and hardener. This accelerates the cure and lessens flow of resin along inclined mold surfaces. The "gel coat" should be brushed on the mold with long even strokes making sure all bubbles are removed. Allow the epoxy to settle for a few minutes then remove any additional bubbles. It usually takes several coats of resin to cover the mold properly. If you are making a curved or angled specimen remove excess resin from corners or grooves; in addition, watch out for thinning out in inclined areas.

If you are working with a polyester resin you will have to be more careful since bubbles may never get a chance to escape during the curing process and tend to get trapped at the surface.

Do not mix the hardener with the resin until you are ready to apply the resin. Never mix more than one quart at a time since gel time will be changed when using resin in larger amounts. Begin with small batches until you have gotten experience with the lay-up process and the application of resin. You will need approximately 100 ml for the gel coat -- 1 1/2 sq. foot panel. For the actual lay-up use about 400 ml. (for a seven-ply 1 square foot specimen). Do not attempt to re-brush an area, particularly after the resin has begun to harden. If the resin in your can shows signs of thickening, discard it and mix another batch. After the complete layup is finished, allow resin to harden. Resin is hard when your fingernail will not make an indentation in the surface.

Once the "gel coat" has dried you should clean it thoroughly with soap and water to remove any oil or dust that may damage the bond with the rest of the specimen. Begin the lay-up by mixing a batch of resin (2 Resin:1 Hardener), making sure it is well mixed and that no bubbles are in the mixture. Apply a coat of resin to the mold and then place a layer of chopped mat on it. The mat should first be rolled, using wax paper to prevent sticking fibers onto the roller, and then coated with more resin. Avoid clumping, air gaps, resin pools for these will affect the quality of your specimen. To apply resin start from center and work out with short rapid brush strokes. The wet finish coat on top of the first layer of mat acts as "bedding" coat for the first layer of cloth. The cloth is applied while the resin is wet. Each

layer is saturated from the bottom in this way, and from the top with additional coats of resin.

Starting at one end of the mold, unroll the cloth, applying the cloth smoothly working out wrinkles as you go; now wet out with resin. Use squeegee to smooth cloth if you prefer, but do not be afraid to use hands; wash hands frequently in bucket of detergent and water or acetone (or simply put on new gloves).

Roll the cloth out evenly to remove all air bubbles, note that the cloth is much easier to roll than the mat since it will not clump up, apply extra pressure to remove any air that may have been trapped in the mat or layers below. Repeat this procedure for all the layers. Finish up with one or two layers of chopped mat. Trim and sand off all whiskers, lumps and extra cloth. The smoother each layer is, the smoother the entire job will be.

Let the fiberglass job stand for at least three days; "blushing" or loosening of coating may develop if placed in the water too soon.

Should air bubbles develop, sand through bubbles after resin has hardened, then fill area with finish coat. Should air bubbles or pockets develop due to the cloth pulling away from the gull (surface not clean), you can cut out the entire area and patch with cloth and resin.

Resin, chopped mat, roving, pigments, etc., can be purchased from Allied Resin Corporation, Weymouth Industrial Park, East Weymouth, Mass. 02189; Tel: (617) 337-6070.

# APPENDIX B. Liquid Crystals

## Cholesteric Liquid Crystals

Liquid crystals are substances which over a clearly defined temperature range appear to possess the flow characteristics of a liquid while retaining much of the molecular order of a crystalline solid. Liquid crystals can be nematic, smectic or cholesteric according to their molecular structures. Cholesteric liquid crystals have parallel molecules whose long axis lies along very thin planes.

The molecular layers in a cholesteric substance are very thin (approximately 3 Angstroms) with the long axes of the molecules parallel to the plane of the layers. The individual molecules are essentially flat, with a side chain of methyl groups (CH3) projecting upward from the plane of each molecule. This unusual configuration causes the direction of the long axes of the molecules in each layer to be displaced slightly from the corresponding direction in adjacent layers. This displacement, which averages about 15 minutes or arc per layer, is cumulative through successive layers, so that the overall displacement traces out a helical path. The pitch of the helical path is usually temperature-dependent, and the temperature dependence may be postive or negative. The twist in the cholesteric molecular structure can be observed in the optical characteristics of homogeneously ordered layers.

The molecular architecture of cholesteric liquid crtystals

gives rise to anumber of peculiar optical properties. As polarized light transmitted perpendicularly to the molecular layer the direction of the electric vector of the light will be rotated progressively to the left along a helical path, thus the plane of polarization which is determine by the electric vector and the direction of poropagation will also be rotated to the left, through an angle that is proportional to the thickness of the transmitting material. Optically active materials, those which rotate light in this fashion, such as certain types of quartz, rotate the plane of polarization about 20 degrees per millimeter and are considered very active. An optically active cholesteric substance, on the other hand, rotates the plane of polarization through an angle of as much as 198,000 degrees, or 50 rotations per millimeter. Liquid crystals of this kind are by far the most optically active substances known.

Another strictly crystalline optical property exhibited by cholesteric liquids is circular dichroism. When ordinary white light is directed at a cholesteric material, the light is separated into two components, one with the electric vector rotating clockwise and the other with the electric vector rotating counter-clockwise. Depending on the material, one of these is transmitted and the other is reflected. It is this property that gives the cholesteric phase its characteristic iridescent color when it is illuminated by white light. The particular combination of colors depends on the material, the temperature and the angle of the incident beam.

Each cholesteric liquid crystal has unique responses to temperature variations. The cholesteric ester structure, the number of carbon atoms in the acid group, determine the temperature range over which the crystals exhibit colors and the colors exhibited during this transition. Liquid crystals may exhibit only a fraction of the color spectrum or they may go through the full spectrum according to their structure. Liquid crystals can be blended to scatter light over a temperature range from -20 degrees to 250 degrees Centigrade. The color-play range (temperatures over which colors are given) can vary from 50 to 1 degree Centigrade, the response time is of the order of 0.1 sec. with a resolution of 0.1 degree Centigrade. The best literature on liquid crystals is covered in the patent literature7. The important parameters that control a liquid crystal's usefulness in non-destructive testing are:

1) availability and cost,
2) ease of application,
3) resistance to wind and UV exposure,
4) dust resistance,
5) long shelf life,
6) reliable color play range, at relevant temperatures.

Prepared liquid crystal blends can be purchased from LCB, Liquid Crystal Biosystems, Inc., 26101 Miles Road, Cleveland, Ohio 44128.

These are available in spray cans and come in four color play ranges: 30-33 degrees Centigrade, 31-34 degrees Centigrade,

32-35 degrees Centigrade, 33-36 degrees Centigrade. The blends are satisfactory for LCT but are not effective for testing thick panels or performing tests where the relevant thermal differences occur above 36 degrees Centigrade. Liquid crystal blends can be made with several organic chemicals available from Kodak and other sources. I experimented with a system of cholesteryl oleyl carbonate and cholesteryl nonanoate and was able to duplicate the color response the blends produced by LCB. I also be prepared blends to operate at the 50 and 60 degrees Centigrade range. The temperature range of canned blends is just a few degrees above room temperature and hence is quite vulnerable to air currents and other forms of convective cooling that affect the accuracy of a test.

Blends should be applied evenly over the entire area to be tested, the thickness of the layer should be about 1 mil, a thinner layer should be used at first, then if the color response was not adequate more crystals should be sprayed on. Select an open area for spraying and place the specimen flat on some newspapers. When spraying avoid covering an area too thickly, use fast strokes from 12-18 inches depending on the spay pattern. When using your own blends be extremely careful with the atomized solvent (hexane, petroleum ether); they are extremely volatile and should not be used indoors, unless there is good ventilation.

Blends for field testing will have to be able to withstand wind and intense light. Using thin crystal films will reduce the amount of distortion when exposed to wind. The use of ultra-

violet stabilizers such as PABA (P-amino benzoic acid) can protect the blends from destruction by UV and can increase their shelf life substantially[7].

The cost of liquid crystal blends varies but is still relatively cheap compared to other NDE tests. Cholesteryl nonanoate is available from Eastman Kodak for 19.05 for 25 g, cholesteryl oleyl carbonate 25 g $49.50. The crystal blends are the most important part of the test and further research should definitely be conducted to develop suitable blends for field testing of fiberglass.

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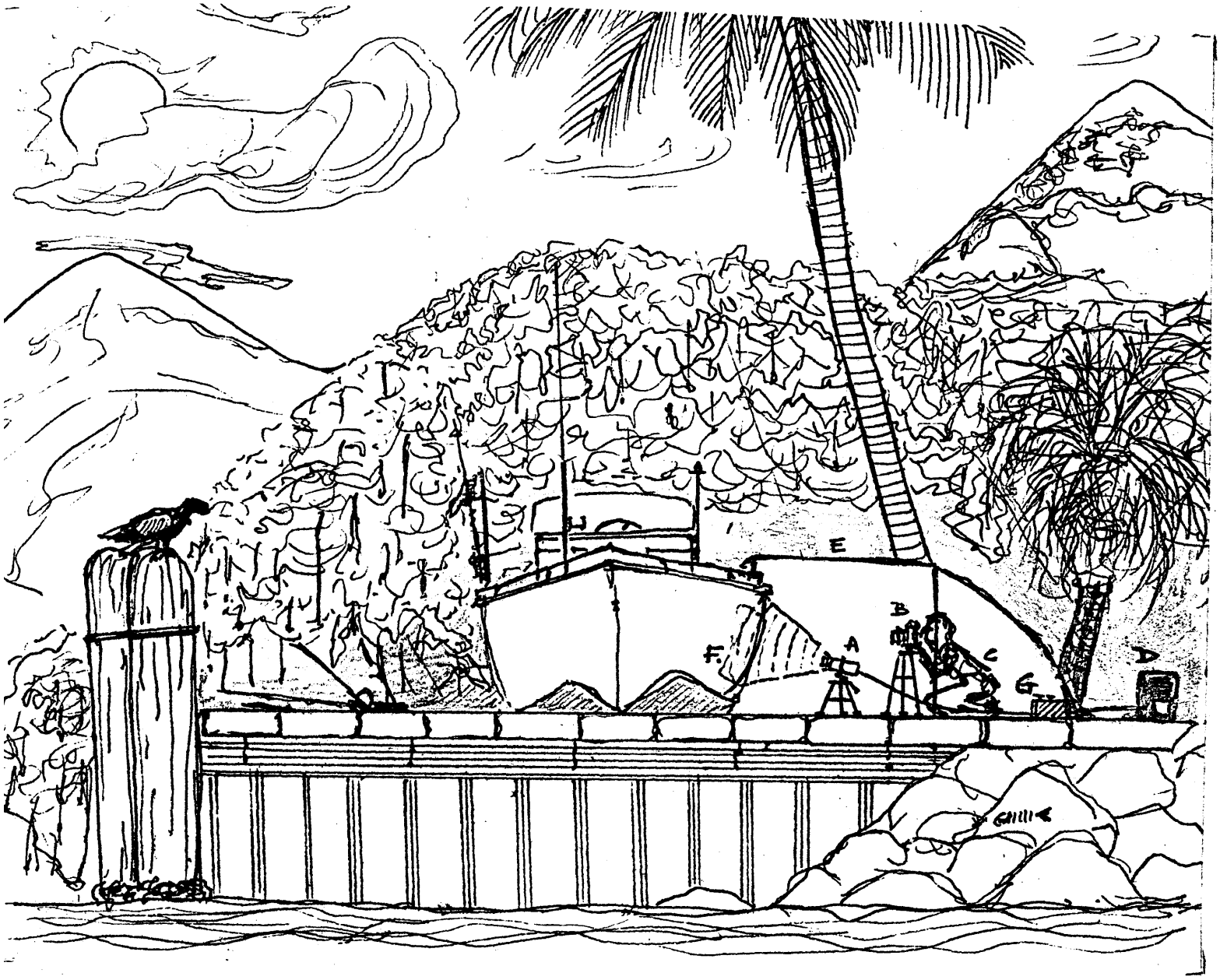



Figure 1. Field testing with cholesteric liquid crystals. This drawing illustrates a possible equipment set-up for on-site testing. A--Regulated frequency and amplitude light source. B--Camera. C--Technician. D--Portable generator. E--Protective tent. F--Boat. G--Instrument box with light controls.

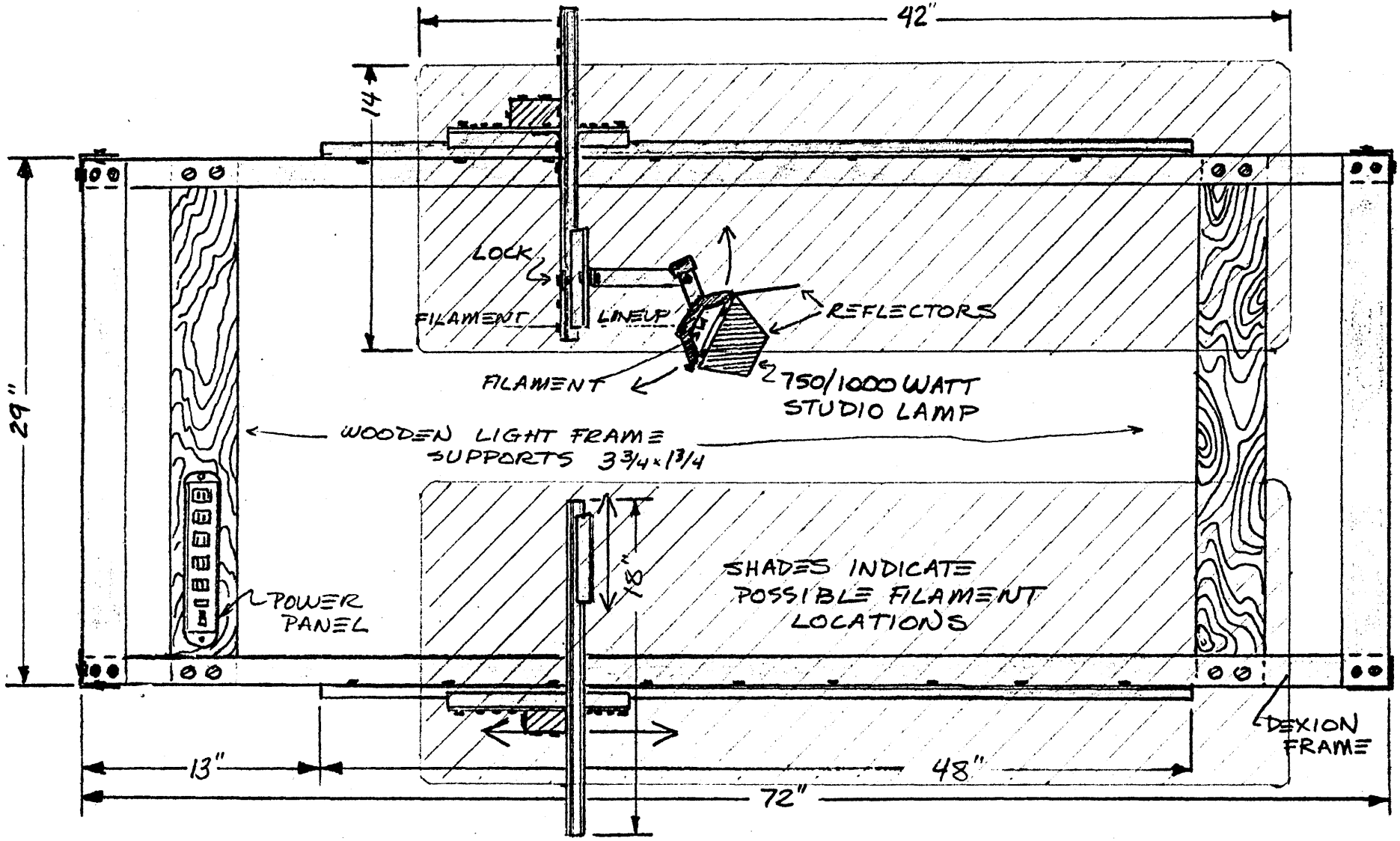



Figure 2. Light jig (top view) this section. Taken at mid-filament. Shows the rails built for this research which permit quick adjustments on the location of the studio lamps. Shaded areas show possible locations for light filaments.

**TABLE 1**

APPROPRIATE NONDESTRUCTIVE EVALUATION METHODS
FOR COMPOSITE MATERIALS

| DEFECT | FIBERGLASS | BORON FIBER | GRAPHITE FIBER |
|---|---|---|---|
| Disbonds | Sonic<br>Ultrasonic<br>Thermal (thin sections only) | Sonic<br>Ultrasonic<br>Thermal (thin sections only)<br>Eddy-Sonic | Sonic<br>Ultrasonic<br>Eddy-Sonic |
| Delaminations | Sonic<br>Ultrasonic<br>Thermal (thin sections only)<br>Thermoluminescent Coatings | Sonic<br>Ultrasonic<br>Thermal (thin sections only)<br>Eddy-Sonic<br>Thermoluminescent Coatings | Sonic<br>Ultrasonic<br>Eddy-Sonic<br>Thermoluminescent Coatings |
| Fiber-Orientation (Tape) | Back-lighting (magnified)<br>X-ray (low kv) | Back-lighting (magnified)<br>X-ray (low kv) | X-ray (low kv) |
| Fiber-Orientation (Laminate) | X-ray<br>Microscope (edge) | X-ray<br>Microscope (edge) | Microscope (edge) |
| Inclusions | X-ray<br>Ultrasonic | X-ray<br>Ultrasonic | X-ray<br>Ultrasonic |
| Crushed Honeycomb Core | X-ray<br>Ultrasonic (through transmission) | X-ray<br>Ultrasonic (through transmission)<br>Eddy-Sonic | X-ray<br>Ultrasonic (through transmission)<br>Eddy-Sonic |
| Resin-rich and resin-starved areas | X-ray<br>Ultrasonic | X-ray<br>Ultrasonic | X-ray<br>Ultrasonic |
| Micromechanic studies | Acoustic emission | Acoustic emission | Acoustic emission |
| Thickness gaging | Micrometer<br>Ultrasonic | Micrometer<br>Ultrasonic | Micrometer<br>Ultrasonic |
| Porosity and cracks (internal) | Ultrasonic<br>X-ray (thin sections only) | Ultrasonic<br>X-ray (thin sections only) | Ultrasonic<br>X-ray (thin sections only) |
| Porosity and cracks (external) | Penetrant | Penetrant | Penetrant |
| Adhesive joint disbonds | Pulse Echo<br>(Also, see disbonds and delaminations above.) | Pulse Echo | Pulse Echo |

| Name | Definition | Visual Acceptance Levels | | |
|---|---|---|---|---|
| | | Level I | Level II | Level III |
| Chip | a small piece broken off an edge or surface | none | maximum dimension of break, 3.0 mm (⅛ in.) | maximum dimension of break, 6.5 mm (¼ in.) |
| Crack | an actual separation of the laminate, visible on opposite surfaces, and extending through the thickness | none | none | none |
| Crack, surface | crack existing only on the surface of the laminate | none | maximum length, 3.0 mm (⅛ in.) | maximum length 6.5 mm (¼ in.) |
| Crazing | fine cracks at or under the surface of a laminate | none | maximum dimension of crazing, 13 mm (½ in.) frequency and location to be determined by customer | maximum dimension of crazing, 25 mm (1 in.) |
| Delamination, edge | separation of the layers of material at the edge of a laminate | none | maximum dimension, 3.0 mm (⅛ in.) | maximum dimension, 6.5 mm (¼ in.) |
| Delamination, internal | separation of the layers of material in a laminate | none | none | none |
| Dry-spot | area of incomplete surface film where the reinforcement has not been wetted with resin | none | maximum diameter, 9.5 mm (⅜ in.) | maximum diameter, 14 mm (9/16 in.) |
| Foreign inclusion (metallic) | metallic particles included in a laminate which are foreign to its composition | none | none, if for electrical use; maximum dimension, 0.8 mm (1/32 in.), 1/0.09 $m^2$ (1 $ft^2$), if for mechanical use | none, if for electrical use; maximum dimension, 1.5 mm (1/16 in.), 1/0.09 $m^2$ (1 $ft^2$), if for mechanical use |
| Foreign inclusion (nonmetallic) | nonmetallic particles of substance included in a laminate which seem foreign to its composition | none | maximum dimension, 0.8 mm (1/32 in.), 1/0.09 $m^2$ (1 $ft^2$) | maximum dimension, 1.5 mm (1/16 in.); 1/0.09 $m^2$ (1 $ft^2$) |
| Fracture | rupture of laminate surface without complete penetration | none | maximum dimension, 21 mm (13/16 in.) | maximum dimension, 29 mm (1⅛ in.) |
| Air bubble (void) | air entrapment within and between the plies of reinforcement, usually spherical in shape | none | maximum diameter, 1.5 mm (1/16 in.); 2/$in.^2$ | maximum diameter, 3.0 mm (⅛ in.); 4/$in.^2$ |
| Blister | rounded elevation of the surface of a laminate, with boundaries that may be more or less sharply defined, somewhat resembling in shape a blister on the human skin | none | maximum diameter, 3.0 mm (⅛ in.); height from surface not to be outside drawing tolerance | maximum diameter, 6.5 mm (¼ in.); height from surface not to be outside drawing tolerance |
| Burned | showing evidence of thermal decomposition through some discoloration, distortion, or destruction of the surface of the laminate | none | none | none |
| Fish-eye | small globular mass which has not blended completely into the surrounding material and is particularly evident in a transparent or translucent material | none | maximum diameter, 9.5 mm (⅜ in.) | maximum diameter, 13 mm (½ in.) |
| Lack of fillout | an area, occurring usually at the edge of a laminated plastic, where the reinforcement has not been wetted with resin | none | maximum diameter, 6.5 mm (¼ in.) | maximum diameter, 9.5 mm (⅜ in.) |



Table 2. Allowable defects. ASTM 2563.

| Name | Definition | Visual Acceptance Levels | | |
|---|---|---|---|---|
| | | Level I | Level II | Level III |
| Orange-peel | uneven surface somewhat resembling an orange peel | none | maximum diameter, 14 mm (9/16 in.) | maximum diameter, 29 mm (1 1/8 in.) |
| Pimple | small, sharp, or conical elevation on the surface of a laminate | none | none | maximum diameter, 3.0 mm (1/8 in.) |
| Pit (pinhole) | small crater in the surface of a laminate, with its width approximately of the same order of magnitude as its depth | none | maximum diameter, 0.4 mm (1/64 in.); depth less than 1 percent of wall thickness | maximum diameter, 0.8 mm (1/32 in.); depth less than 20 percent of wall thickness |
| Porosity (pinhole) | presence of numerous visible pits (pinholes) | none | frequency and location to be determined by customer; maximum of 25 pits (pinholes) in porous area of size listed in Level II | maximum of 50 pits (pinholes) in porous area of size listed in Level III |
| Pre-gel | an unintentional extra layer of cured resin on part of the surface of the laminate (This condition does not include gel coats.) | none | maximum dimension, 6.5 mm (1/4 in.); height above surface not to be outside drawing tolerance | maximum dimension, 13 mm (1/2 in.); height above surface not to be outside drawing tolerance |
| Resin-pocket | an apparent accumulation of excess resin in a small localized area within the laminate | none | maximum diameter, 3.0 mm (1/8 in.) | maximum diameter, 6.5 mm (1/4 in.) |
| Resin-rich edge | insufficient reinforcing material at the edge of molded laminate | none | maximum, 0.4 mm (1/64 in.) from the edge | maximum, 0.8 mm (1/32 in.) from the edge |
| Shrink-mark (sink) | depression in the surface of a molded laminate where it has retracted from the mold | none | maximum diameter, 9.5 mm (3/8 in.); depth not greater than 25 percent of wall thickness | maximum diameter, 14 mm (9/16 in.); depth not greater than 25 percent of wall thickness |
| Wash | area where the reinforcement of molded plastic has moved inadvertently during closure of the mold resulting in resin-rich areas | none | maximum dimension 21 mm (13/16 in.) | maximum dimension 29 mm (1 1/8 in.) |
| Wormhole | elongated air entrapment which is either in or near the surface of a laminate and may be covered by a thin film of cured resin | none | maximum diameter, 3.0 mm (1/8 in.) | maximum diameter, 6.5 mm (1/4 in.) |
| Wrinkles | in a laminate, an imperfection that has the appearance of a wave molded into one or more plies of fabric or other reinforcement material | none | maximum length surface side, 13 mm (1/2 in.); maximum length opposite side, 13 mm (1/2 in.); depth less than 10 percent of wall thickness | maximum length surface side, 25 mm (1 in.); maximum length opposite side, 25 mm (1 in.); depth less than 15 percent of wall thickness |
| Scratch | shallow mark, groove, furrow, or channel caused by improper handling or storage | none | maximum length, 25 mm (1.0 in.); maximum depth, 0.125 (0.005 in.) | maximum length, 25 mm (1.0 in.); maximum depth, 0.255 (0.010 in.) |
| Short | in a laminate, an incompletely filled out condition NOTE—this may be evident either through an absence of surface film in some areas, or as lighter unfused particles of material showing through a covering surface film, possibly accompanied by thin-skinned blisters | none | none | none |



Table 2 (cont.). Allowable defects. ASTM 2563.

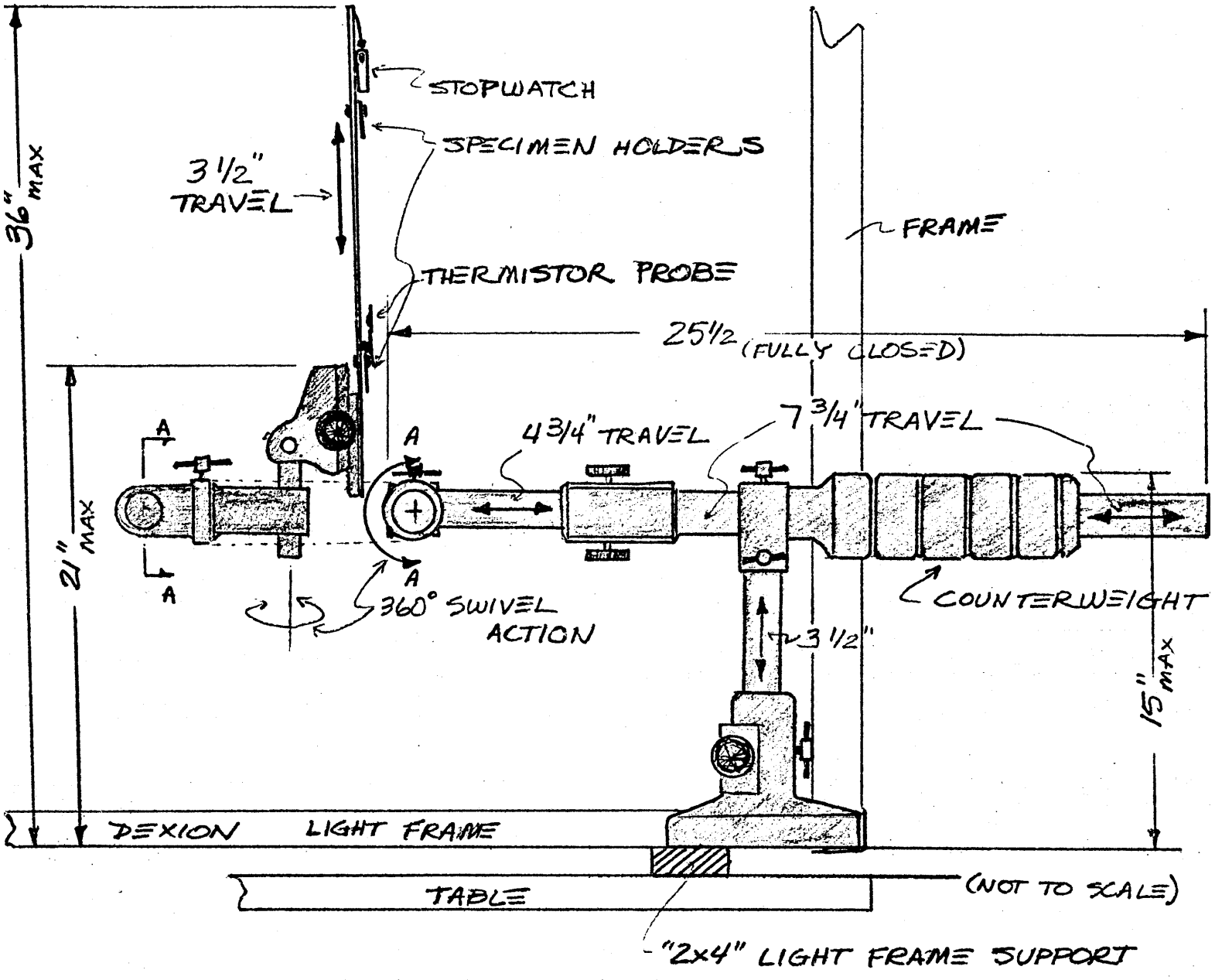
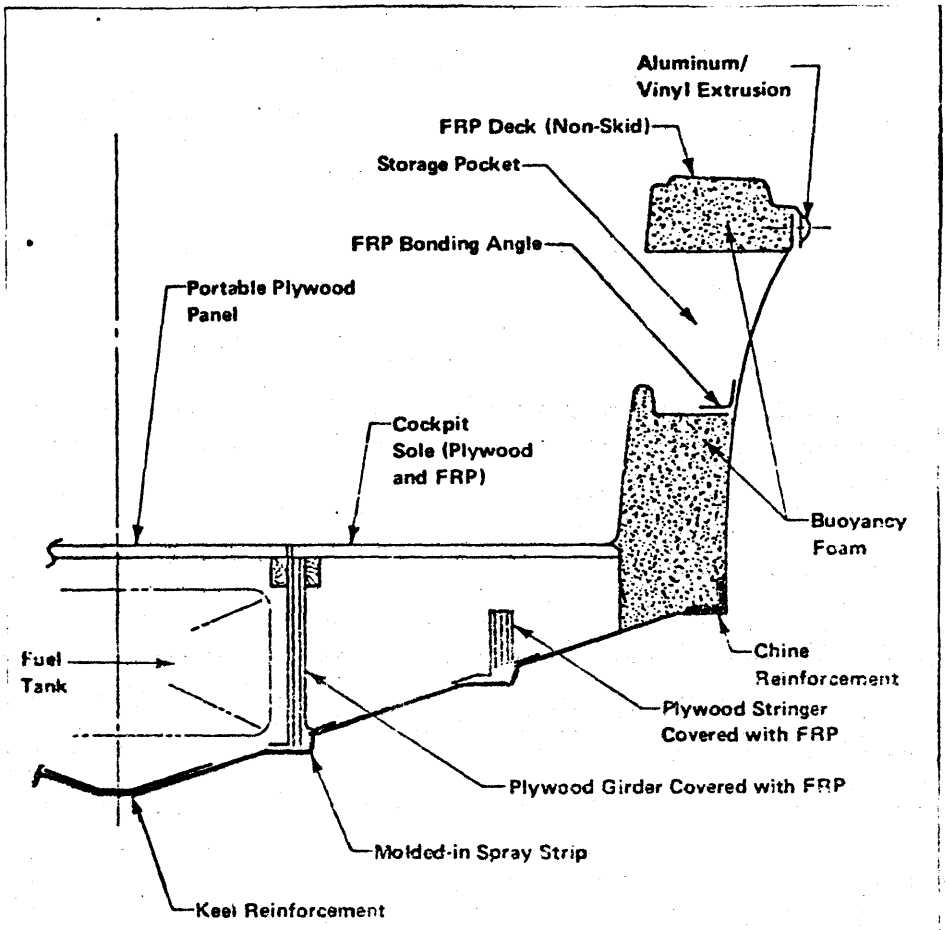



Figure 3. Specimen holder. This drawing shows the range of settings for the specimen holder.




Inboard/Outboard Power Cruiser

Figure 4. Deep vee hull section.[6]

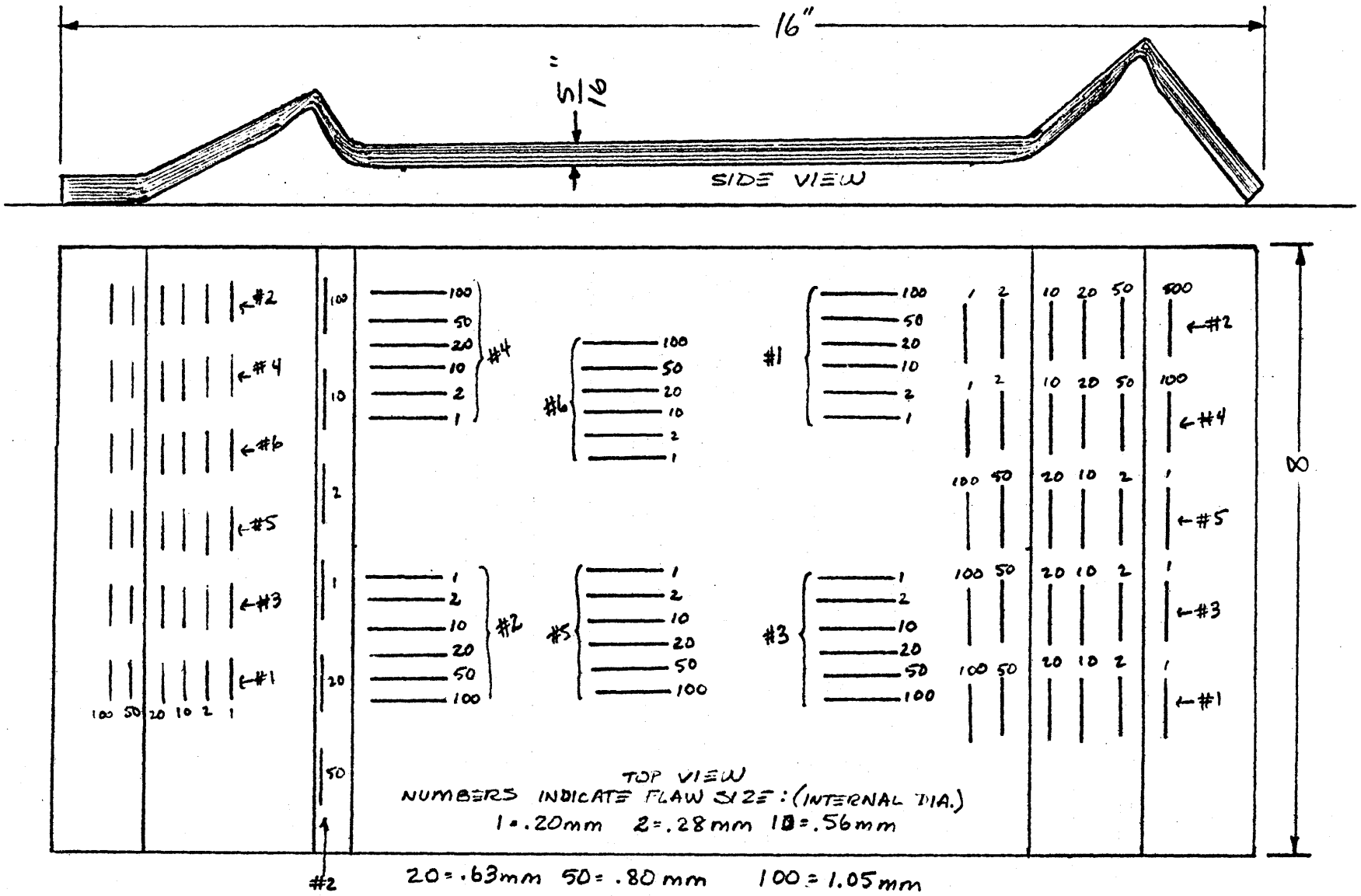



Figure 5. Fiberglass panel showing approximate flaw locations.

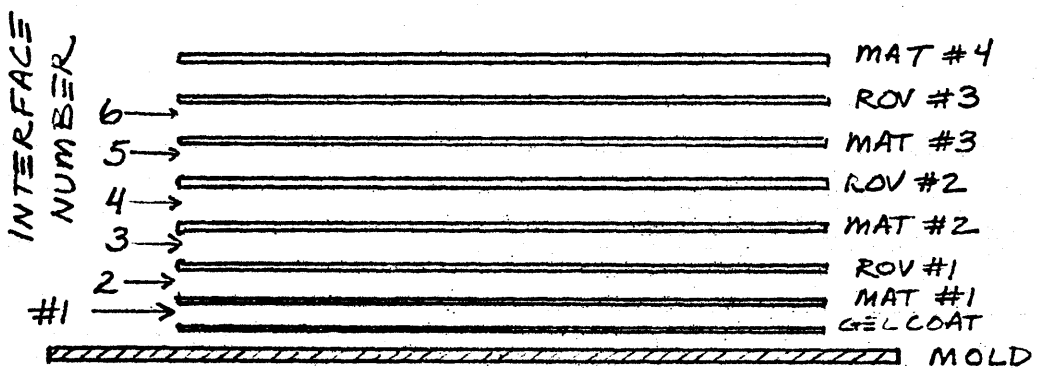



Figure 6. Interface coding sequence used to record flaw locations.

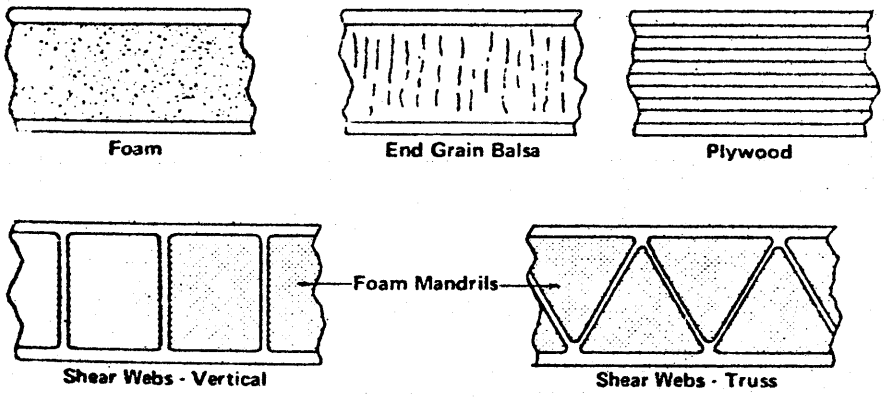



Figure 7. Core materials.[6]

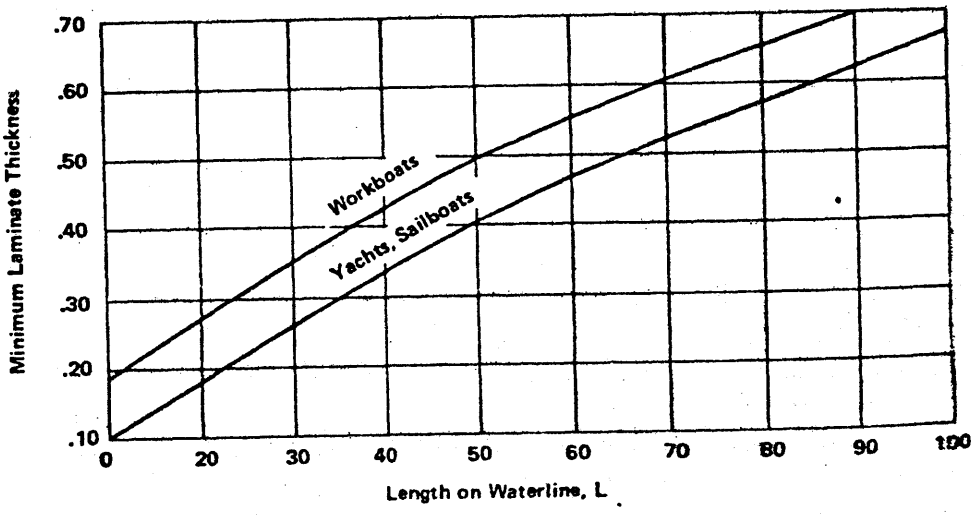



Table 3. Typical hull thickness.[6]

## Number of Plies or Pairs vs Laminate Thickness in Inches

| *Laminate* | *Glass Content (Percent)* | | *Number of Plies or Pairs* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* |
| 1-1/2 oz. Mat. | 20 | Low | .060 | .120 | .180 | .240 | .300 | .360 | .420 | .480 | .540 | .600 | .660 | .720 | .780 | .840 | .900 |
| | | High | .076 | .152 | .228 | .304 | .380 | .456 | .532 | .608 | .684 | .760 | .836 | .912 | .988 | 1.064 | 1.140 |
| | 25 | Low | .045 | .090 | .135 | .180 | .225 | .270 | .315 | .360 | .405 | .450 | .495 | .540 | .585 | .630 | .675 |
| | | High | .061 | .122 | .183 | .244 | .305 | .366 | .427 | .488 | .549 | .610 | .671 | .732 | .793 | .854 | .915 |
| | 30 | Low | .035 | .070 | .105 | .140 | .175 | .210 | .245 | .280 | .315 | .350 | .385 | .420 | .455 | .490 | .525 |
| | | High | .050 | .100 | .150 | .200 | .250 | .300 | .350 | .400 | .450 | .500 | .550 | .600 | .650 | .700 | .750 |
| Composite Laminate (Alternate Plies of 1-1/2 oz. Mat and 24 oz. WR) | 30 | Low | .110 | .220 | .330 | .440 | .550 | .660 | .770 | .880 | .990 | 1.100 | 1.210 | 1.320 | 1.430 | 1.540 | 1.650 |
| | | High | .126 | .252 | .378 | .504 | .630 | .756 | .882 | 1.008 | 1.134 | 1.260 | 1.386 | 1.512 | 1.638 | 1.764 | 1.890 |
| | 35 | Low | .090 | .180 | .270 | .360 | .450 | .540 | .630 | .720 | .810 | .900 | .990 | 1.080 | 1.170 | 1.260 | 1.350 |
| | | High | .107 | .214 | .321 | .428 | .535 | .642 | .749 | .856 | .963 | 1.070 | 1.177 | 1.284 | 1.391 | 1.498 | 1.605 |
| | 40 | Low | .075 | .150 | .225 | .300 | .375 | .450 | .525 | .600 | .675 | .750 | .825 | .900 | .975 | 1.050 | 1.125 |
| | | High | .091 | .182 | .273 | .364 | .455 | .546 | .637 | .728 | .819 | .910 | 1.001 | 1.092 | 1.183 | 1.274 | 1.365 |
| 24 oz. Woven Roving | 40 | Low | .045 | .090 | .135 | .180 | .225 | .270 | .315 | .360 | .405 | .450 | .475 | .540 | .585 | .630 | .675 |
| | | High | .061 | .122 | .183 | .244 | .305 | .366 | .427 | .488 | .549 | .610 | .671 | .732 | .793 | .854 | .915 |
| | 45 | Low | .038 | .076 | .114 | .152 | .190 | .228 | .266 | .304 | .342 | .380 | .418 | .456 | .494 | .532 | .570 |
| | | High | .054 | .108 | .162 | .216 | .270 | .324 | .378 | .432 | .486 | .540 | .594 | .648 | .702 | .756 | .810 |
| | 50 | Low | .032 | .064 | .096 | .128 | .160 | .192 | .224 | .256 | .288 | .320 | .352 | .384 | .416 | .448 | .480 |
| | | High | .048 | .096 | .144 | .192 | .240 | .288 | .336 | .384 | .432 | .480 | .528 | .576 | .624 | .672 | .720 |
| | 55 | Low | .027 | .054 | .081 | .108 | .135 | .162 | .189 | .216 | .243 | .270 | .297 | .324 | .351 | .378 | .405 |
| | | High | .042 | .084 | .126 | .168 | .210 | .252 | .294 | .336 | .378 | .420 | .462 | .504 | .546 | .588 | .630 |
| | 60 | Low | .023 | .046 | .069 | .092 | .115 | .138 | .161 | .184 | .207 | .230 | .253 | .276 | .299 | .322 | .345 |
| | | High | .038 | .076 | .114 | .152 | .190 | .228 | .266 | .304 | .342 | .380 | .418 | .456 | .494 | .532 | .570 |

Table 4.6

Number of Plies or Pairs vs.
Laminate Weight Pounds Per Square Foot

| *Laminate* | *Glass Content (Percent)* | | *Number of Plies or Pairs* | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* |
| 1-1/2 oz. Mat | 20 | Low | .439 | .878 | 1.32 | 1.76 | 2.20 | 2.63 | 3.07 | 3.51 | 3.95 | 4.39 | 4.83 | 5.27 | 5.71 | 6.15 | 6.59 |
| | | High | .499 | .998 | 1.50 | 2.00 | 2.50 | 2.99 | 3.49 | 3.99 | 4.49 | 4.99 | 5.49 | 5.99 | 6.49 | 6.99 | 7.49 |
| | 25 | Low | .345 | .690 | 1.04 | 1.38 | 1.73 | 2.07 | 2.42 | 2.76 | 3.11 | 3.45 | 3.80 | 4.14 | 4.49 | 4.83 | 5.18 |
| | | High | .405 | .810 | 1.22 | 1.62 | 2.03 | 2.43 | 2.84 | 3.24 | 3.65 | 4.05 | 4.46 | 4.86 | 5.27 | 5.67 | 6.08 |
| | 30 | Low | .283 | .566 | .849 | 1.13 | 1.42 | 1.70 | 1.98 | 2.26 | 2.55 | 2.83 | 3.11 | 3.40 | 3.68 | 3.96 | 4.25 |
| | | High | .343 | .686 | 1.03 | 1.37 | 1.72 | 2.06 | 2.40 | 2.74 | 3.09 | 3.43 | 3.77 | 4.12 | 4.46 | 4.80 | 5.15 |
| Composite Laminate (Alternate Plies of 1-1/2 oz. Mat and 24 oz. WR) | 30 | Low | .823 | 1.65 | 2.47 | 3.29 | 4.12 | 4.94 | 5.76 | 6.58 | 7.41 | 8.23 | 9.05 | 9.88 | 10.7 | 11.5 | 12.3 |
| | | High | .913 | 1.83 | 2.74 | 3.65 | 4.57 | 5.48 | 6.39 | 7.30 | 8.22 | 9.13 | 10.0 | 11.0 | 11.9 | 12.8 | 13.7 |
| | 35 | Low | .700 | 1.40 | 2.10 | 2.80 | 3.50 | 4.20 | 4.90 | 5.60 | 6.30 | 7.00 | 7.70 | 8.40 | 9.10 | 9.80 | 10.5 |
| | | High | .789 | 1.58 | 2.37 | 3.16 | 3.95 | 4.73 | 5.52 | 6.31 | 7.10 | 7.89 | 8.68 | 9.47 | 10.3 | 11.0 | 11.8 |
| | 40 | Low | .606 | 1.21 | 1.82 | 2.42 | 3.03 | 3.64 | 4.24 | 4.85 | 5.45 | 6.06 | 6.67 | 7.27 | 7.88 | 8.48 | 9.09 |
| | | High | .696 | 1.39 | 2.09 | 2.78 | 3.48 | 4.18 | 4.87 | 5.57 | 6.26 | 6.96 | 7.66 | 8.35 | 9.05 | 9.74 | 10.4 |
| 24 oz. Woven Roving | 40 | Low | .403 | .806 | 1.21 | 1.61 | 2.02 | 2.42 | 2.82 | 3.22 | 3.63 | 4.03 | 4.43 | 4.84 | 5.24 | 5.64 | 6.05 |
| | | High | .430 | .860 | 1.29 | 1.72 | 2.15 | 2.58 | 3.01 | 3.44 | 3.87 | 4.30 | 4.73 | 5.16 | 5.59 | 6.02 | 6.45 |
| | 45 | Low | .357 | .714 | 1.07 | 1.43 | 1.79 | 2.14 | 2.50 | 2.86 | 3.21 | 3.57 | 3.93 | 4.28 | 4.64 | 5.00 | 5.36 |
| | | High | .383 | .766 | 1.15 | 1.53 | 1.92 | 2.30 | 2.68 | 3.06 | 3.45 | 3.83 | 4.21 | 4.60 | 4.98 | 5.36 | 5.75 |
| | 50 | Low | .320 | .640 | .960 | 1.28 | 1.60 | 1.92 | 2.24 | 2.56 | 2.88 | 3.20 | 3.52 | 3.84 | 4.16 | 4.48 | 4.80 |
| | | High | .347 | .694 | 1.04 | 1.39 | 1.74 | 2.08 | 2.43 | 2.78 | 3.12 | 3.47 | 3.82 | 4.16 | 4.51 | 4.86 | 5.21 |
| | 55 | Low | .290 | .580 | .870 | 1.16 | 1.45 | 1.74 | 2.03 | 2.32 | 2.61 | 2.90 | 3.19 | 3.48 | 3.77 | 4.06 | 4.35 |
| | | High | .316 | .632 | .948 | 1.26 | 1.58 | 1.90 | 2.21 | 2.53 | 2.84 | 3.16 | 3.48 | 3.79 | 4.11 | 4.42 | 4.74 |
| | 60 | Low | .265 | .530 | .795 | 1.06 | 1.33 | 1.59 | 1.86 | 2.12 | 2.39 | 2.65 | 2.92 | 3.18 | 3.45 | 3.71 | 3.98 |
| | | High | .292 | .584 | .876 | 1.17 | 1.46 | 1.75 | 2.04 | 2.34 | 2.63 | 2.92 | 3.21 | 3.50 | 3.80 | 4.09 | 4.38 |

Table 5.6